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Fabrication of Ni-Al Alloy Transpiration-Cooling Device by Powder-Metallurgical Microchanneling Process

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Abstract
We examine a concept and fabrication method of a microchannel-type transpiration-cooling device consisting of thermally resistant metals. The device consists of open-porous Ni-Al alloys and contains microchannel networks. Cooling water is supplied from a tank to every corner of the device through the microchannel networks, and then it seeps out to be vaporized absorbing the latent heat. The porous body of the device and the microchannel are produced by a powder-metallurgical microchanneling process using a sacrificial core.

Key words
Microchannel, Powder Metallurgy, Transpiration Cooling, Nickel Aluminide, Porous Material, Robot

1. Introduction

Transpiration cooling is known as one of the most effective cooling methods and it is expected to be applied to a space rocket or a disaster preventing robot [1-3]. In the latter case, cooling water is delivered via the feed space, and then the water seeps out to the surface of the robot to be vaporized absorbing the latent heat of evaporation. This system makes it possible to protect the electronic device from the environmental heat efficiently. In order to design for parts with complicated geometry such as a joint of arms, we proposed a novel transpiration-cooling system. [4] Figure 1 presents the schema of this system. An intricately shaped portion consists of porous metal and contains microchannel networks. The microchannel networks act as flow passages for the cooling water just as veins in plant leaves or blood vessels in animal bodies. And then the cooling water seeps out to the surface like sweat. With this system, designing the complicated portions of the robot will be easier.

In order to produce such a porous device, we examined a powder-metallurgical microchanneling process [5-8]. Figure 2 illustrates the formation mechanism of the microchannel. In this process, two kinds of metals with different melting points are used: the body-metal which has a higher melting point and is to compose the device body, and the sacrificial-core metal which is to be fused and give the shape of the microchannel. Body-metal powder containing a sacrificial core is sintered at temperatures between the melting points of the metals. During sintering, molten sacrificial-core metal migrates to the body-metal region by infiltration and diffusion. As a result, a microchannel is formed at the sites initially occupied by the sacrificial-core metal. In addition, an alloy lining layer surrounding the microchannel often forms.

In the previous paper [4], we reported the possibility of the microchannel-type transpiration-cooling method using

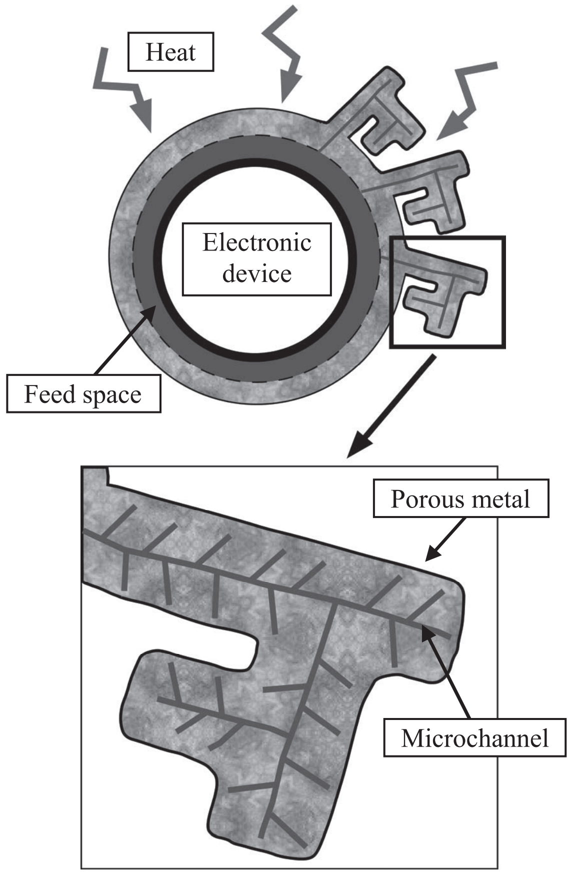

Fig. 1 Schema of the transpiration-cooling system

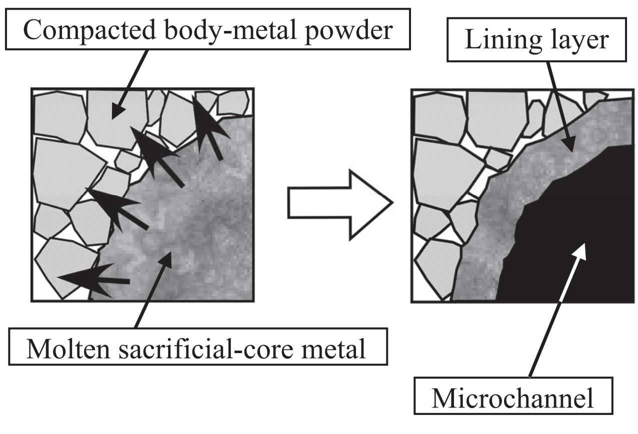

Fig. 2 Schematic illustration of the concept of the powder-metallurgical microchanneling process

a combination of copper and zinc as a model system. Figure 3 shows the result of a water-flow examination. Seeping water at the surface of the specimen was observed.

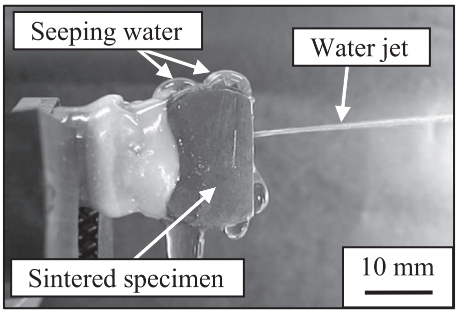

Fig. 3 Flow examination for a Cu-Zn specimen.[4] The green compact was pressed under 30 MPa

For practical purposes, however, thermal resistance, oxidation resistance and corrosion resistance are required for the outer-shell materials. Intermetallic compounds such as NiAl and Ni_3Al have these properties. These intermetallic compounds can be produced from the elemental powders by powder-metallurgical methods such as combustion synthesis and reaction sintering. Furthermore, porous products are easily produced by these methods. [9-11] For conventional use, such a porous product is a critical defective. However, it is the material just desired for our purpose. In other words, the problem can be changed into the advantage.

Based on these backgrounds, we investigated the possibility of the process to produce such a thermally-resistant transpiration-cooling device consisting of porous Ni-Al alloys.

2. Experimental Procedure

2.1 Fabrication of powder compact and microchanneling heat treatment

A cylindrical Ni-Al mixed powder compact containing Al wire was prepared by unidirectional pressing at room temperature. The molar ratio of Ni and Al powders was fixed to be 3:1. A straight Al wire 500 μm in diameter and 10 mm in length was used as the sacrificial core. The compacting pressure was varied from 100 to 690 MPa. Figure 4 shows the relationship between the compacting pressure and the initial porosity of the compact specimen before sintering. As shown in this figure, the porosity was controlled by the compacting pressure.

The standard heat-treatment pattern was set at as follows. The specimens were heated at a constant rate of 0.3 K/s from room temperature to 1173 K, and then they were kept at 1173 K for 10.8 ks before furnace-cooled at about 0.1 K/s. In the case when an abrupt temperature rise was observed during heating, which was an indication of the combustion synthesis reaction, energizing to the furnace was stopped and the specimen was naturally cooled in the furnace. In the other case, the sintering behavior was viewed as an ordinary reaction sintering.

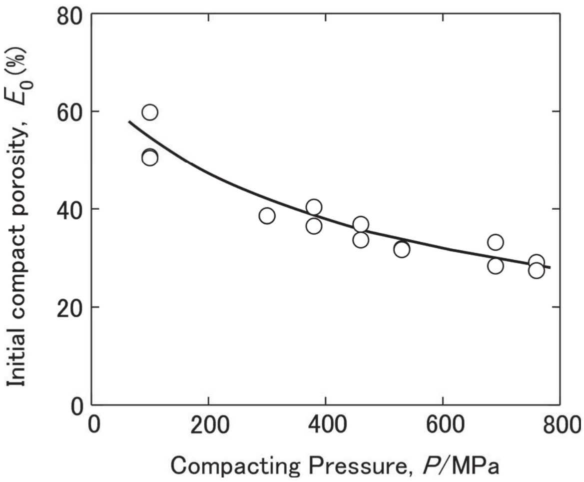

Fig.4 Relationship between the compacting pressure and the initial porosity of the compact specimen

2.2 Water-flow examination

Figure 5 depicts a schematic illustration of the specimen for the flow examination. A 40-mm-long Al wire was shaped into a zigzag configuration for the sacrificial core. The mass of the Ni-Al mixed powder was 10 g. The molar ratio of Ni and Al powders were fixed to be 3:1. The compacting pressure was 100 MPa. The obtained powder compact had a diameter of 20 mm, and a height of about 8.5 mm. After the heat treatment, both ends of the microchannel were exposed, and one end was connected with a copper pipe 1 mm in inner diameter. The copper pipe and the specimen were joined using a Cu fitting and

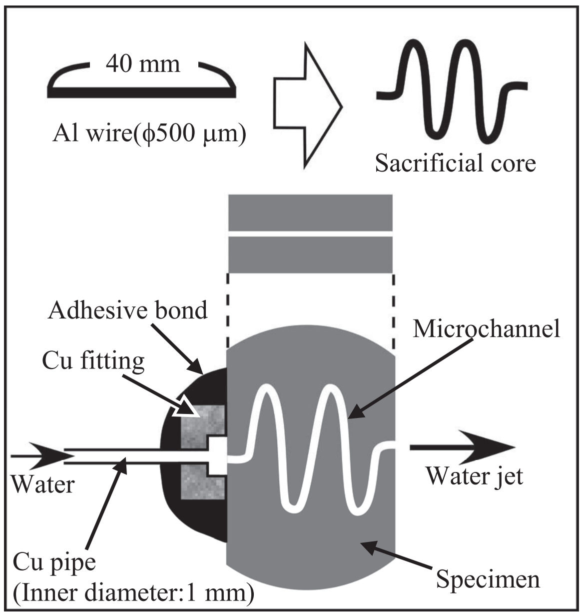

Fig. 5 Schema of the specimen for the flow examination

an epoxy adhesive bond. Water was injected into the microchannel through the copper pipe. The water jet from the outlet of the microchannel and seeping water on the surface of the specimen were observed.

3. Results

3.1 Influence of the compacting pressure on the formation of the microchannel

In the case when the compacting pressure was 300 MPa or higher, the combustion synthesis reaction occurred at a temperature near the melting point of Al during heating. Typical macrostructure of the combustion-synthesized specimen was shown in Fig. 6. In this photograph, large shrinkage defects are observed at the center of the specimen. This part was probably a hot spot caused by the combustion synthesis reaction with an abrupt and large heat evolution. There was no distinct microchannel in this specimen. It might have been incorporated into a shrinkage defect.

In the case when the compacting pressure was 100 MPa, by contrast, no rapid temperature change was observed. The specimen was reaction-sintered probably because the apparent thermal conductivity of the compacted body-metal powder was not sufficiently high for self-propagation of the exothermic synthesis reaction. In this condition, an open microchannel was produced. Figure 7 shows a cross-sectional microstructure near the microchannel. As shown in this photograph, the microchannel is surrounded by a porous structure. In the case of reaction sintering, many new pores were formed at the sites initially occupied by the Al powder particles. This result indicates that the structure required for the transpiration-cooling device can be produced by reaction sintering.

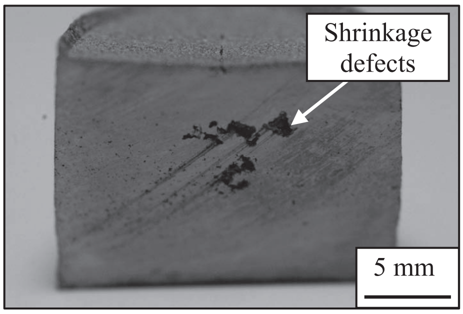

Fig. 6 Macrostructure of a combustion-synthesized specimen. Compacting pressure was 530 MPa

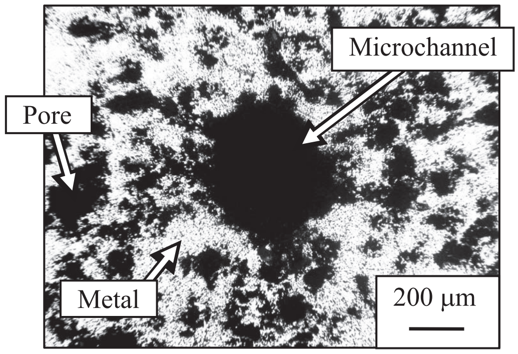

Fig. 7 Microstructure near the microchannel in a Ni-Al reaction-sintered specimen. Compacting pressure was 100 MPa

3.2 Result of water-flow examination

Figure 8 presents the result of the water-flow examination of the reaction-sintered specimen. A water jet from the outlet of the microchannel and seeping water on the entire surface of the specimen were observed. This indicates that the long zigzag microchannel was open throughout the length and our concept of the thermally-resistant Ni-Al alloy transpiration-cooling device is realizable. The water jet was observed when the water pressure was 1.5 kPa or higher. On the other hand, the minimum water pressure for seeping of water was 20.0 kPa.

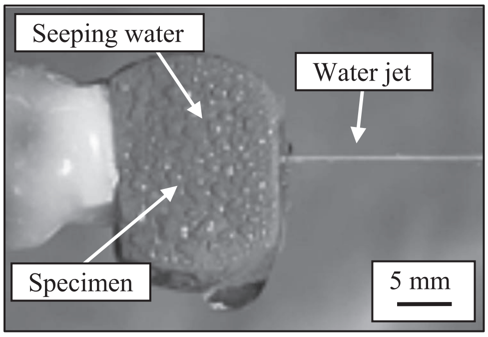

Fig. 8 Flow examination for a Ni-Al reaction-sintered specimen. Water flow rate was 2.5×10^{-6} m^3s^{-1}

3.3 Porosity distribution inside the specimen

In the water-flow examination using the Cu-Zn specimen, the seeping water was observed only at the lateral face of the columnar specimen but at the base end surfaces (see Fig. 3). [4] The cause of this phenomenon can be explained by percolation theory [12]. This theory says that the porosity higher than 30 % is necessary for infiltration of water in three-dimensional porous media. In the Cu-Zn specimen, the porosity near the base end surfaces fell below 30 %. These results agree with the percolation theory.

Figure 9 depicts the porosity profiles in the reaction-sintered Ni-Al specimen. The porosity was measured by image analysis on optical micrographs. Position of the origin (x= 0) was set at the center of the specimen. Unlike the Cu-Zn specimen, all the measured data were over 30 %. These results correspond to the fact that seeping water was observed on the entire surface of the specimen.

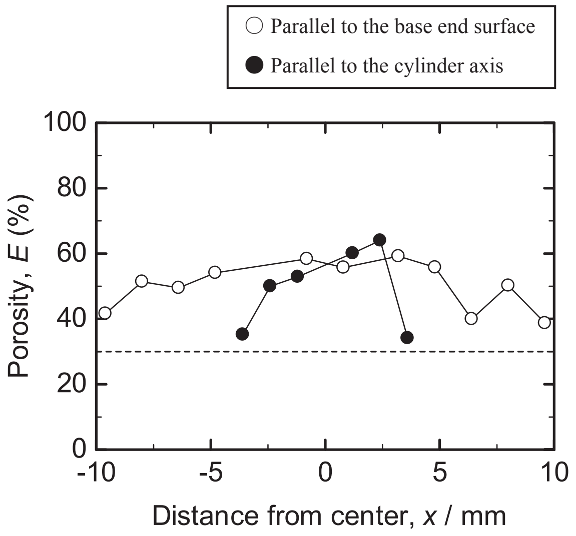

Fig. 9 Porosity distributions in a Ni-Al reaction-sintered specimen

4. Conclusions

(1) In the case when the compacting pressure was 300 MPa or higher, the combustion synthesis reaction occurred in the course of heating. As a result, large shrinkage defects evolved and damaged the device.

(2) In the case when the compacting pressure was 100 MPa, the specimen was reaction-sintered and an open microchannel was produced.

(3) In the water-flow examination of the reaction-sintered specimen, seeping water on the entire surface of the specimen was observed.

(4) According to the porosity distribution inside the reaction-sintered specimen, all the measured data were over 30 %.

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